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Chapter 24

HL-LHC IT String and Hardware Commissioning

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The HL-LHC IT String is the test stand to validate the collective behavior of the Inner Triplet (IT) magnets and circuits in conditions as near as possible to the operational ones.

1. Introduction

The HL-LHC project's goal is to upgrade the present LHC machine through modification and replacement of parts of the existing accelerator by new technologies that enable HL-LHC to reach its goals [1]. To reduce the risks associated to such upgrade and to these innovative technologies, all major components are tested individually at CERN or at collaborators' premises. The individual component tests are, however, not totally representative of their behavior in the machine, as the magnets and other major components connect in the HL-LHC in a common electrical and cooling circuit through which they may interact with each other. Therefore, the HL-LHC IT String installation, in an existing surface building, allows the validation and testing of a complete Inner Triplet (IT) region of the HL-LHC under nominal working conditions, checking the collective behavior of its components [2]. The HL-LHC IT String is a major intermediate milestone for the HiLumi project that will also allow the verification of a system integration and a smoother hardware commissioning of the final machine, installed in the underground areas.

2. Description of the HL-LHC IT String

The HL-LHC IT String, located in the SM18 (the CERN Magnet Test Facility building), will represent the IT zone of the left side of HL-LHC Point 5 with the exception of the inclination of the tunnel that will be not represented in the IT STRING bringing the difference between the Point 5 and Point 1 to be negligible. The IT STRING will not include the matching section region modified for HL-LHC.

2.1. *The magnets of the HL-LHC IT String*

The HL-LHC IT String will be composed by the Q1, Q2a, Q2b, Q3 (all together called the IT quadrupoles), the CP (magnet Corrector Package) and the D1 (separation dipole) cryo-magnet assemblies. These cryo-magnets contain more than one magnet each: a total of 21 superconducting magnets using NbTi- or Nb_3Sn-based technology will be required to set-up the test stand.

2.2. *Powering*

In the HL-LHC IT String, as for the HL-LHC tunnel installations, the magnets are powered via a Superconducting Link System, referred to as Sc link hereafter, composed mainly by the MgB_2 link and the current leads that use high temperature superconducting cables. On one side, the Sc link is connected to the magnets and on the other side to the room temperature DC connections. In both cases, interface devices, the so-called DFX and DFHX respectively, are setup to properly perform the connections. The leads are linked to the power converters via copper bus-bars, water-cooled cables or air-cooled cables (WCC/ACC), depending on the circuit. As in the HL-LHC, the so-called Circuit Disconnector Boxes (CDB) will be installed between the power converters and the Sc link system allowing fast and safe disconnection of the circuits from the powering system in case of needed intervention. Although the main circuits could be powered with converters presently used for the testing of main LHC magnets and already installed in the test hall, the IT String will be powered with new higher precision 2 quadrant power converters through the Sc link, exactly as planned in the HL-LHC operation. The Sc link will be the first of the series production. The WCC or ACC linking the power converters, the circuit disconnector boxes and the current leads will be adapted in their length to cope with the particularity of the integration of the IT zone into the surface building.

2.3. *Cryogenic cooling*

The cooling of the magnets is done via a dedicated cryogenic valve box, installed for this purpose in the existing test facility. It will allow the HL-LHC IT String test stand to be connected to the global cryogenic system of the test hall and thus to cool down the magnets to superfluid helium temperature. The Sc Link will be cooled with helium gas generated in the DFX on the magnet side. The gas will flow through the High Temperature Superconducting system, including the current leads. Finally, it will be recovered at room temperature, near the DFHX, and sent back to the cryogenic system. The magnets are designed to work at 1.9 K, cooled with superfluid helium. The HL-LHC IT String cooling is independent from the cooling of the rest of the SM18 test facility, where both individual magnets and Radio Frequency (RF) cavities will be under qualification tests in parallel to the IT String operation. Although the cooling and pumping capacities were increased to cover the total need of the tests, thanks to the common efforts of the HL-LHC project and the TE department, a close coordination of the tests and the IT String operation will be necessary during the operation. In its final configuration, the test stands, and so the HL-LHC IT String will be able to profit from a 35 g/s liquid helium production and 12 g/s pumping capacity. The most demanding events in terms of cooling during the hardware commissioning of the IT String or during the study phase -quenching of the magnets- are likely to happen during extended working hours, leaving the possibility to re-cool the system to the operational temperature during the night. The total energy dumped into the He bath can be as high as 39 MJ [3] in case the circuits are powered and quenched at ultimate current. This energy is mostly coming from the circuits of the Q1-Q3 magnets.

2.4. *Circuit protection*

The magnet and circuit protection of the HL-LHC IT String will be the same as in the tunnel, as one of the major goals of the test stand is to verify the protection efficiency and confirm the working principles. The protection against quenches (sudden transitions from superconducting to normal state) is assured by a detection system and a reaction one. Concerning the quench detection system, this is built on the same logic of the units installed in the LHC, but it is based on a new and more powerful generation of electronics. As for the reaction system, three types of elements are used: coil active heating, energy extraction and bypass diodes. The systems combination depends on the circuits and the characteristics of each of them. One of the most innovative protection elements is the CLIQ discharge system, which, acting directly on the magnet conductor, allows the rapid and uniform warm up of the magnets during quench events. In such cases, these units of capacitor banks are discharged directly into the magnets, using the heat generated by the coupling current in the Rutherford cables to quench and evenly distribute the warm up to the entire magnet. This method is combined with the more classical way of protection, in which heater strips integrated into the magnet coils are heated up by the discharge of capacitor banks, with the result of a more homogenous and faster distribution of the quench area. The heater strips (called quench heaters), besides providing redundancy to CLIQ at intermediate and high currents, are necessary for protection at low current.

The energy extraction system is used only for corrector magnets and consists of a switching element that allows dissipating the inductive energy stored in the magnets into an external dump resistor. The bypass diodes are integrated into the inner triplet magnets and allow to route the current in an alternative path during quenches.

2.5. *Alignment system*

In the framework of the HL-LHC project, an innovative alignment system has been developed to perform a fully remote precise positioning, monitoring and realignment of the magnets, allowing more frequent alignment campaigns while minimizing the dose exposure to personnel working in the tunnel [4]. This new system will monitor the position of the cold masses in the cryostat guiding the adjustment through motorized jacks. The distance measurements will be done by Frequency Scanning Interferometry (FSI). To determine the position of the cold mass in the cryostat the system will use 14 Wire

Positioning Sensors (WPS), 18 Hydrostatic Levelling Sensors (HLS) and 6 sensors for the longitudinal position. Despite the many similarities between the IT String test and the final configuration in the LHC, the inclination in the tunnel will not be implemented in the IT String as none of the component owners considered it necessary. The experience acquired by operating the magnets with the LHC slope is reckoned sufficient, also by the most affected system, i.e. cryogenics, to design, build and operate the new IT zone without testing it in the IT String.

2.6. *Vacuum system*

The major difference between the HL-LHC IT zone and the IT String is the vacuum system. The HL-LHC IT String, in fact, will not be equipped with beam screens. This decision was taken in order to achieve the maximum cost optimization for the test installation without sacrificing essential measurements [5]. It was judged that the learning of the LHC and some off-line test on individual magnets and validations in the laboratory can entirely address the questions related to the beam screen. These tests have been performed on model magnets, and therefore in time for fine-tuning the system if necessary. Hence, the design of the vacuum system aims to have a common beam and insulation vacuum.

3. HL-LHC IT String Validation Program

3.1. *Performance test of components before installation*

Each component will be tested individually before its installation in the IT String. In particular, the magnets are tested at the collaborators' premises and/or at CERN at nominal operational conditions. For example, the individual magnets will be powered up to nominal current, and to ultimate if required by the testing protocol. At each step of the test, their electrical integrity will be checked.

In general, acceptance and qualification test of the components are under the responsibility of each work package. The IT String test aims to complement them, as a system test.

3.2. *Electrical circuit integrity test*

The Electrical Quality Assurance (ElQA) [6] tests will be performed to assess the integrity of the dielectric insulation of the circuits and will be done at predefined and agreed levels of voltage for each circuit and during all steps of assembly and cool-down. The integrity of the instrumentation and protection systems wiring will be verified. The IT String allows to test the revised and adapted ElQA procedures for the HL-LHC.

3.3. *Cryogenic system test*

The cryogenic system test will focus on the cool down of the magnet chain and the thermal behaviour, after a quench, of the cold and warm powering systems, composed of the magnets, bus-bars, cold diodes, Sc links, cold boxes, current leads, alignment systems, warm cables and power converters. The ultimate heat load capacity for individual test of each pair of heat exchangers is evaluated to be 500 W for Q1-Q2a and Q2b-Q3 and 250 W for D1-CP. The main objective of the cryogenic tests is to get advanced information on the cryogenic characteristics of the cold mass cooling system, the quench relief system and on transient effects.

3.4. *Vacuum system test*

The IT String design does not include beam screens and therefore there is no test planned to verify heat deposition. Those verifications will be addressed with independent studies. The insulation vacuum will be qualified through a leak test with different sealing options. The other singularity of the vacuum system of the IT String, i.e. the single vacuum region for both beam screen and cryostat, may be the most important deviation from the operational configuration. The experience accumulated with LHC is applicable to the HL-LHC IT String and allowed to make this decision, and thus reducing the costs for the IT String [5].

3.5. *Powering of the IT magnets*

The HL-LHC will require the development of new high precision power converters as well as energy storage systems for the 18 kA power converters that have never been used in the LHC. The magnets will be powered individually or in series (for the Q1 to Q3 assembly) where the fields of Q1, Q1a and Q3 will be adjusted with trim circuits. The IT String will be the first and unique occasion to test the series powering before the commissioning in the tunnel. The IT String test is the occasion to validate the crowbar circuit system and the impact of flux jumps on current regulation and precision.

The cold powering system is composed mainly of the HTS current leads and the Sc link, which relies on cooling with helium gas. The gas has a temperature range from 4.2 K up to 35 K - 50 K. The use of MgB_2 and HTS materials enables safe operation of the superconducting components, for which a temperature margin of at least 10 K is guaranteed. Although the Sc link will go through qualification tests, the IT String setup will also validate the lambda plate in its final configuration, and the connection between the warm powering, cold powering, and magnet systems through superconducting bus-bars and other equipment. The complete warm and cold powering systems will only be tested in the IT String before their installation into the LHC tunnel.

3.6. *Quench detection and Magnet protection system test*

A careful detection and protection system test is performed before powering the magnets at low and intermediate current. For Nb_3Sn magnets in particular, the appearance of flux jumps was found in the low and medium current range, with amplitudes ranging from 10 mV up to 2 V, and characteristic times of 10 to 20 ms. The quench detection is based on electronics called Universal Quench Detection System (uQDS), as planned for HL-LHC. This system is tested on the magnet test benches and set up to cope with the flux jumps, but the cross-talk between magnets in the Sc link hosting the various feeding cables may amplify flux jumps effect and thus trigger the protection system unnecessarily. These events, called trips, imply in most cases a non-negligible loss of machine availability, as triggering the magnet protection implies heat deposition into the cryo-magnets. Similarly, the protection of the magnets is relying on the quench heaters and the DAQ and control system that are only tested on a magnet circuit in the HL-LHC IT String before its very first installation in the tunnel.

To qualify the systems approximately 200 quenches at different energy levels are planned.

3.7. *Powering interlock test*

The interlock system validation will be one of the most critical tests. The HL-LHC interlock will integrate and handle, with a given logic, signals from all subsystems. The overall system test will only be possible in the IT String, as the interlock system used on the benches for the test of individual cryo-magnet assemblies is a dedicated one, not necessarily working in the same conditions as in the tunnel.

3.8. *Alignment system test*

The required accuracy of the relative positioning of the cryostats is in the order of magnitude of micrometers with an absolute alignment error of ±0.1 mm with respect to the referential system of SM18. The complete system test is essential, as it is the very first time that the FSI based system is used in a chain of magnets and in real installation and working conditions. The test will confirm the alignment repeatability of cryostats with respect to an external reference, validate the full remote alignment and monitoring systems before ordering the series systems, and allow the study of the impact of vacuum or cold conditions.

3.9. *DAQ test*

In general, every system will have its associated Data Acquisition (DAQ) system and control system. The debugging of those systems is done in the IT String, aiming to improve the efficiency during hardware commissioning. The communication between systems and the data exchange for the good diagnostics of the events will be one of the major goals of the IT String. Dedicated DAQ or control software for the HL-LHC IT String are not foreseen, but rather those that are already used in the LHC or their updated version for the HL-LHC.

3.10. *Performance tests*

The aim of the performance tests will be to investigate the capability of the different subsystems to work together and within the specified conditions.

The HL-LHC IT String test plan includes the powering up to nominal current values and a complete thermal cycle of the circuits.

3.11. *Quality assurance*

The IT String will give the opportunity to validate and test all Quality Control (QC) steps, as well as installation and test procedures.

4. The HL-LHC IT String in the SM18 Test Hall

The SM18 facility (building 2173 at CERN) was the host building for the LHC String 1 [7] and String 2 [8] test installations and for the testing of the LHC magnets prior to installation in the tunnel. For the 3rd time, the facility is the place where this String experiment will be installed and operated.

The choice of the place was essentially based on the available installations and infrastructures that would allow such a test. The project included a significant contribution to the upgrade of several systems, although not dimensioned for the simultaneous HL-LHC IT String operation and full component testing at the same time. A space of 120 m length is available as of 2021 to begin the installation of the test stand. Both primary and demineralized water system, together with the electrical network, were upgraded with a joint effort of the HL-LHC project and the TE department completed in 2019. A major upgrade of the cryogenic cooling system for an additional 35 g/s liquid helium production capacity started in 2019. These modifications allow the parallel test of the individual components both for magnets, and RF systems in the same building [9]. An important coordination and scheduling work will be required during the IT String operation as the pumping capacity remains limited to 12 g/s.

Figure 1 illustrates the integration of the HL-LHC IT String test stand in the SM18 hall and Figure 2 illustrates in detail the aforementioned components of the String.

5. The HL-LHC IT String Timeline

One of the main goals of the IT String is to test and confirm the nominal operational conditions and the ***collective behavior*** of the entire IT setup, before

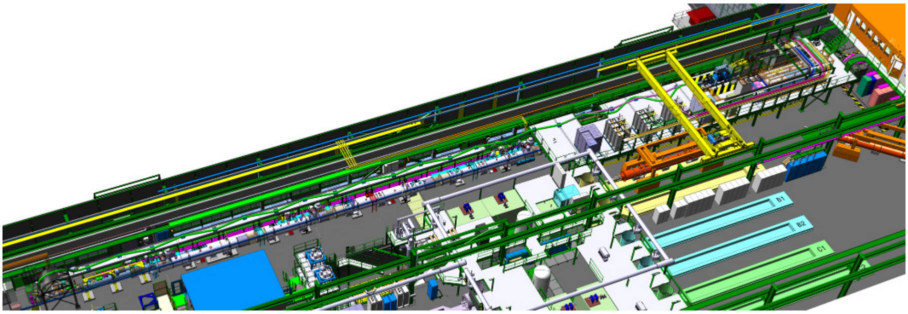

Fig. 1. The HL-LHC IT String in the SM18 hall.

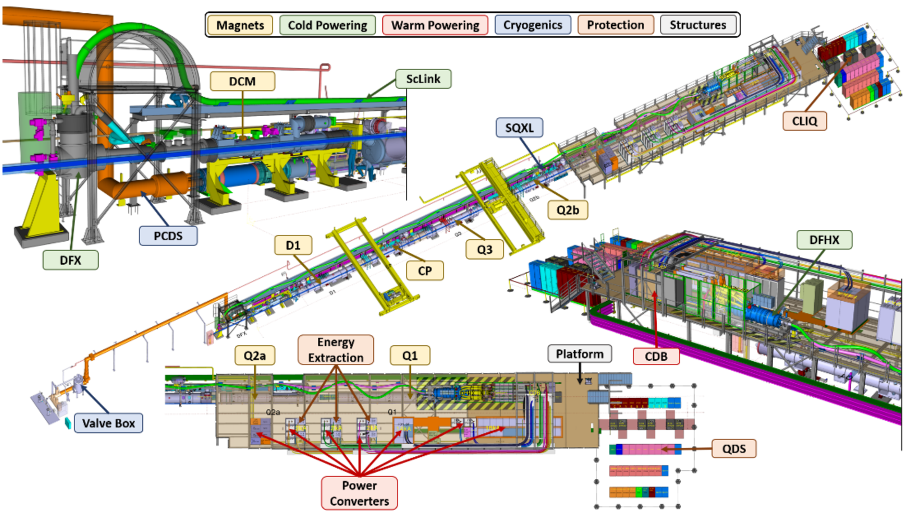

Fig. 2. Components of the HL-LHC IT String.

the installation of the magnets and main components in the LHC tunnel. The delivery schedule of the cold masses, around mid-2022, is the key element defining the critical path of the installation, which will start in 2021. The cryogenic distribution system should be ready by the end of 2021, as well as the metallic structure, allowing the placement of the powering system on top of the magnets, an interesting disposition from both safety and space allocation point of view. The IT String will be prepared for an effective operation of at least 1 year. The operation period could be extended by 4 months, dedicated to a complete thermal cycle and operation to ultimate conditions. The HL-LHC

IT String will be ready for dismounting before the end of 2024 with the option of an extension of the test plan.

6. Hardware Commissioning

6.1. *Commissioning of the superconducting circuits*

6.1.1. *Electrical Quality Assurance tests*

As stated in [10], the objective of the ElQA tests is to validate each individual superconducting circuit before powering, to gather all the necessary electrical parameters for operation, and to track all the data acquired and to manage the related non-conformities.

ElQA at warm

At the end of the installation and connection of all magnets and the superconducting link, resistance measurements and a high voltage qualification of all circuits will be performed: to check whether the circuit is closed and all instrumentation sound, determine a reference resistance value at warm, and to validate the galvanic insulation versus ground (and coil vs quench heaters, for those magnets with quench heaters). The values of voltages to be applied and the maximum acceptable leakage current values are being finalised [11-17].

ElQA at cold

Similar tests will be performed at cold, with larger test voltages applied. The circuits and the corresponding link will be cooled down to their nominal temperature. For the high voltage qualification of all lines, this will be performed to validate the galvanic insulation versus ground and the capacity of all lines to withstand the mutual high voltages developed during a fast change of current in the different circuits (typically during a fast abort or quench). The high voltage qualification also includes testing of all the elements that are electrically connected to the tested circuit. Such elements are:

- the instrumentation and feedthrough systems
- the magnet protection units
- the temperature sensors with the related tunnel cabling and electronics

- the tunnel cabling for routing the voltage taps used for the protection of the superconducting circuits.

In addition, impedance measurements will be performed, with the aim of determining the impedance of the magnet systems as a function of the frequency. The results of these measurements are used to spot possible inter-turn shorts, and for determining the settings to adjust the power converter regulation.

6.1.2. *Powering tests*

The HL-LHC magnets present several peculiarities [18] that have to be kept in mind for their commissioning. The most relevant are: the fact that all magnets will be cooled down to 1.9 K; that Nb_3Sn will be used extensively for the first time; that the current of the inner triplet will be the highest in the machine (18 kA); and, importantly, that some of the high current magnets will be protected only via energy extraction in a dump resistor without quench heaters. In addition, the powering scheme of the inner triplet will be different from the present one with implications in case of a quench of one of the magnets. The HL-LHC baseline foresees 11 T magnets in the DS, where NbTi and Nb_3Sn magnets will be powered in series, with the addition of a trim (locally connected to the 11 T magnets via resistive, 120A-like current leads) to compensate for the different transfer functions, with important implications on the powering and the protection of the circuit [19].

The powering of all circuits up to nominal current will be done in steps. At the end of each step, online and offline analyses are performed by equipment owners and protection experts to assess the performance of all hardware in the circuit. In particular, for the powering of individual circuits, several cycles at different current levels will be performed to study the performance of the magnets, the efficiency of the protection mechanisms (by provoking fast aborts and even quenches), and to checks all functionalities of the powering interlocks and of the power converters (via provoked powering failures). A typical series of tests includes:

- at minimum operational current, testing of the full interlock chain, with the verification of cryogenic signals, power permit, powering failure, circuit quench transmission, and fast power abort requests;

- at low current, a check of the power converter performance and verification of all protection functionalities, by means of provoked slow and fast power aborts, with energy extraction;
- repetition of a series of power aborts and, possibly, simulation of quenches from progressively higher current levels, with increasing stored energy (e.g. 25%, 50%, and 100% of the stored energy at nominal current).

Before starting a new powering test, all previous tests must have been validated. The validation includes approval by power converter and powering interlock experts, magnet owners, and protection experts. Cryogenics experts should also confirm the correct operation of their installations and instrumentation. The criteria for approval, the parameters, and the relevant information to be stored will be discussed in due time. The first time that these procedures will be applied is during the test of a full string of magnets (reproducing from Q1 to D1), powered by a superconducting link. All valuable data extracted from the test on the IT String will help to adapt and improve the powering procedure steps and criteria to be used in the LHC tunnel.

After the individual test of all circuits up to the design current, the common powering of a set of circuits will be done for magnets that are in the same cryogenic envelope and are powered from the same link (usually referred to as the powering of a group of circuits). The objective of this powering is to validate the simultaneous operation of all magnets in nominal conditions; current cycles similar to those applied in normal operation should be used for the powering of a group of circuits. What is important at this stage is the behavior with combined powering in critical conditions, such as the fast power abort of a circuit when the others are at full current. For the inner triplets, in particular, quenching of a triplet quadrupole might induce a quench in a nearby quadrupole or corrector magnet if the current in this related circuit is not extracted fast enough. These tests should be performed on all the magnets and could even trigger the change of detection thresholds and protection configurations. Once more, all tests should be approved by a group of experts and recorded for future reference. Particular attention also has to be paid to those circuits that are not equipped with heaters and are protected by energy extraction on a dump resistor. For such circuits, a precise estimate of the energy absorbed by the cold mass during a quench has to be made, not only in the case of standalone operation on the bench tests, but also in the more severe conditions of combined powering in the tunnel. Eventually, the protection threshold should be adapted to reduce energy deposition in the coils and improve magnet safety during powering.

6.1.3. *Magnet training*

Operations at 7 TeV should be established during Run 3. In the process, extensive experience will be gained with the dipole training required to get to the requisite current level. The effects of a full thermal cycle will also be given by the commissioning following the Long Shutdown 2 (LS2). A sound estimate of the number of quenches required after the LS3 will hence be possible and well optimized procedures will be in place to assure an effective retraining campaign. Nevertheless, few information is available for the (re-)training of the Nb_3Sn magnets; extremely useful data should come from the String in this respect. Sufficient time should be foreseen in the schedule for the training to 7 TeV.

6.2. *Hardware commissioning of the HL collimation system*

The mechanics and controls of the collimation system should be identical to that of the Run 3 configuration and required tools should be well debugged and validated by the time of the HL-LHC. The collimator settings, controls and operational sequences should be intensively re-tested during the hardware commissioning phase. A dedicated test to address the reproducibility of collimator movements during critical operational sequences (such as the ramp) will be performed. Before any beam is injected into the machine, the machine protection (MP) functionality of the collimation system must be guaranteed. Each collimator is connected to the beam interlock system (BIS) and has more than 20 interlocks that will need to be verified. The jaw positions and collimator gaps are monitored via six linear variable differential transformer (LVDT) sensors. These signals are interlocked with inner and outer limit values, making a total of 12 interlocks per collimator. In addition, there are a total of six energy-dependent and β*-dependent limit functions and an interlock to protect from 'local' mode collimation control. The temperature of the collimators is also monitored and interlocked with minimum and maximum adjustable settings.

The main upgrade of the collimation system for HL-LHC will ensure cleaning of beam halo and will keep losses in high luminosity experimental regions at an appropriate level. For this, the project foresees the installation of local collimation in the dispersion suppressors. The installation of the new collimators (TCLDs) around Point 2 (made possible by the replacement of the connection cryostats by new ones incorporating the collimators) should be completed by the end of the LS2 and the eventual installation of TCLDs between two 11 T dipoles at point 7 (the cryo-assembly will replace one conventional LHC dipole) could be completed by the end of the LS3. These collimators feature the latest design improvements, including embedded BPMs for fast alignment. Unlike other hardware commissioning tests (such as for the magnets), most of the collimation commissioning will not impact the length of the shutdown, since the tests are individually executed in the shadow of other activities (the main exception being the testing of the interlock system where the BIS needs to be available).

6.3. *Commissioning of the cryogenic systems*

The HL-LHC foresees numerous modifications of the cryogenic system [20]. Among them are:

- the power upgrade for IR1 and IR5;
- the upgrade of the cooling capacity for Sector 3-4 (Sector 4-5 requires less cooling requirements as compared to Sector 3-4 thanks to the new HL infrastructure at P5) to compensate for the additional heat loads of the SRF in P4;
- the new cooling system for the superconducting links;
- the cooling loop for the crab cavities.

The operation of all systems, together with the time needed to qualify and tune the systems, will be detailed later. Provisionally, an approximate time of three weeks is considered to be mandatory to commission the scheme for the superconducting magnets.

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